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A re-appraisal on intensification of biogas production

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ABSTRACT

Biogas is said to be a clean and renewable form of energy. It can replace fossil fuel, thereby eliminating environmental concerns caused by them. Due to several constraints in the process of anaerobic digestion, the potential of this technology is not fully utilized. This paper reviews various techniques like co-digestion, pre-treatments, use of additives, variation in control parameters etc, which could be used to intensify the production of biogas.

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1. Introduction

Millions of tons of solid wastes are generated each year from industrial, agricultural and municipal sources. The municipal solid waste (MSW) generated worldwide is exceeded 2 billion tons/year at the turn of the millennium [1]. Among biological treatments, anaerobic digestion is the most cost-effective, due to the high energy recovered linked to the process and its limited environmental impact [2]. Anaerobic digestion (AD) of organic wastes to produce methane would benefit society by providing a clean fuel from renewable feed stocks. This could substitute fossil fuel-derived energy and reduce environmental impacts including global warming and acid rain [3,4].

Biogas generation has further relevance for tropical, under-developed countries in view of the fact that optimum gas generation activity commences around 30–35 °C, temperatures not easily available in colder regions of the world [5].

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Anaerobic digestion is a multistep microbial process mediated by functionally different microbial groups-saccharide and amino acid fermenters, volatile fatty acid oxidizers and methanogens [6].

2. Biochemical process

Methane fermentation is a complex process, which can be divided into four phases: hydrolysis, acidogenesis, acetogenesis/dehydrogenation, and methanation. Hydrolytic bacteria bring about initial degradation of complex biopolymers such as cellulose, hemicelluloses, proteins and lipids into dicarboxylic acids, volatile fatty acids (VFAs), ammonia, carbon dioxide, hydrogen, etc. Methanogenic bacteria play a key role in the terminal step of anaerobic digestion which uses only a few compounds like acetate, methanol, methylamine, hydrogen and carbon dioxide. VFA and dicarboxylic acids are thus needed to be converted as much as possible to acetate, hydrogen and carbon dioxide for maximum production of methane. This is brought about by hydrogen producing acetogenic bacteria which grows only in syntrophic association with hydrogen scavengers such as sulfate reducing or methanogenic bacteria [7].

Gujer and Zehnder [8] have explained the stages of methane fermentation process as given in Fig. 1.

3. Biogas production enhancement techniques

Anaerobic digestion was considered earlier as a valuable treatment, resulting in reduction of sludge volume, destruction of pathogenic organisms, stabilization of the sludge and production of an energy-rich biogas. However the technique has several limitations like very long retention times (20–30 days) and a low overall degradation efficiency of the organic dry solids (30%–50%). These limitations can be overcome by several enhancement techniques discussed below leading to increased biogas production.

3.1. Co-digestion

Co-digestion is a process in which two or more organic waste materials are digested together in a reactor, thereby improving anaerobic digestion. It shows a higher degradation of organics than the individual processes. Co-digestion improves biogas yield due to the positive synergism established in the digestion medium and the supply of missing nutrients by the co-substrates.

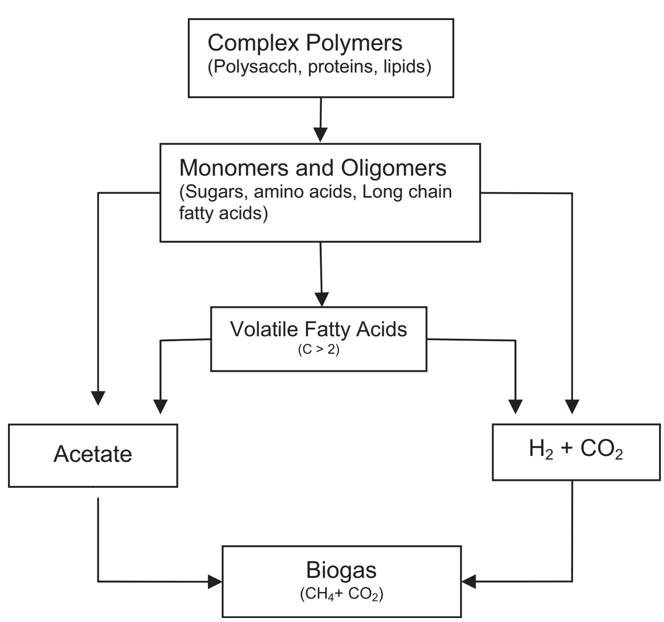

Fig. 1. Stages of the methane fermentation process [8].

According to Davidsson et al. [9] co-digested grease sludge and wastewater treatment plant (WWTP) sludge increases the methane production in the grease trap sludge in comparison to single substrate digestion. Further adding source-sorted organic fraction of municipal solid waste SSOFMSW (20% of the total volatile solids) gives a 10%–15% higher yield which could be expected by comparison with separate digestion of sludge. Elango et al. [10] found that biogas generation was enhanced by the addition of domestic sewage to municipal solid waste (MSW). The maximum biogas production of 0.36 m^3/kg of VS added per day occurred at the optimum organic feeding rate of 2.9 kg of VS/m^3/day. The favorable environment created by the addition of MSW and domestic sewage can explain this enhancement. MSW increases the microorganism's population while addition of domestic sewage increases the concentration of available soluble substrate required by the microorganisms. Carucci et al. [11] observed that co-digestion of the fresh vegetable waste and sludge (60 and 40% on wet basis) allowed methanogenesis up to 53% yield after 114 days with respect to the single wastes (fresh vegetable waste 7.3% and sludge 27.1%). Anaerobic co-digestion of fruit and vegetable waste and sewage sludge by Rizk et al. [12] showed the biogas generation of 331 l in 105 days from a 70 l capacity bioreactor. In an experiment by Ponsá et al. [13], vegetable oil (VO), animal fats (AFs), cellulose and protein (protein) were used as pure co-substrates with organic fraction of municipal solid wastes (OFMSWs). All four co-substrates used led to some operative improvements in digesters used. Fernández et al. [14] found anaerobic co-digestion of organic fraction of municipal solid wastes (OFMSWs) and fat wastes to be a suitable technology to treat such wastes, obtaining a renewable source of energy from biogas.

Gómez et al. [15] claimed that the results for co-digestion of mixtures of primary sludge and fruit and vegetable fraction of municipal solid wastes are better than those obtained from digestion of primary sludge alone. Anaerobic digestion of cattle slurry with fruit and vegetable wastes and chicken manure was conducted by Callaghan et al. On increasing the proportion of fruit and vegetable waste from 20% to 50% improved the methane yield from 0.23 to 0.45 m^3 CH_4/kg VS added, and caused the VS reduction to decrease slightly [16].

Experiments by Kacprzak et al. [17] showed that a combination of three substrates: corn silage, cheese whey, and glycerin fraction resulted in the highest methane content equal to 61% and the biogas production rate of 1.8 L/L/d. When rice or wheat straw was added to cattle dung slurry and digested anaerobically, daily gas production increased from 176 to 331 l/kg total solids with 100% rice straw and to 194 l/kg total solids with 40% wheat straw [18].

Trujillo et al. [19] presented their study of the continuous anaerobic digestion of different mixtures of tomato-plant wastes and rabbit wastes diluted with water. The addition of the tomato-plant wastes to the rabbit wastes in proportions higher than 40% improved the methane production.

Addition of microbial mixed cultures enhanced the anaerobic digestion of Nile perch fish processing wastewater (FPW) with an increment in methane yield of 76% after 12 h of incubation. Co-digestion of the wastewater with brewery wastewater optimally enhanced methane yield to an increment of 66% [20]. Addition of mustard oil cake (MOC) (*Brassica compestries*) to cattle dung digesters showed 63.44% increase in biogas production compared with only cattle dung [21]. Research results obtained by Frigon et al. showed that replacement of 20% of the dairy manure by switchgrass (wetweight) yielded 32% more methane, and the gain was 92% if compared with the raw manure. The amount of methane was then

nearly doubled with the addition of a blending pretreatment to the manure and switch grass [22].

3.2. Digester design

The performance of digester is an important key for enhancing biogas yield. Based on technical performance, anaerobic digesters can be distinguished into one-stage, two-stage and batch systems. Two-phase digester is superior to single phase due to its better control over the operational parameters and bacterial communities. Their greatest advantage lies in the buffering of the organic loading rate taking place in the first stage, allowing a more constant feeding rate of the methanogenic second stage. Therefore the main advantage of two-stage systems is greater biological reliability for wastes which cause unstable performance in one-stage systems.

Bouallagui et al. [23] used a continuous two phase digester for anaerobic digestion of fruit and vegetable waste. Using this system involving a thermophilic liquefaction reactor and a mesophilic anaerobic filter, over 95% volatile solids were converted to methane at a volumetric loading rate of 5.65 g VS/l d. The average methane production yield was about 420 l/kg added VS. Anaerobic membrane bioreactor and online ultrasonic equipment used to enhance membrane filtration were coupled to form a hybrid system (US-AnMBR) designed for long-term digestion of waste activated sludge. The final loading rate of the reactor was determined to be 2.7 g VS/L d with 51.3% volatile solids destruction. Improved digestion in US-AnMBR was due to enhanced sludge disintegration. Ultrasound controlled the membrane fouling development effectively. [24]. The Two-phase anaerobic digestion process with injection of CO_2 exhibits efficient biomass degradation (58% VSS reduction), increased VFA production during the acidogenic phase (leading to VFA concentration of 8.4 g/L) and high biomethane production (0.350 S m^3/kg SSV; 0.363 S m^3/m^3react · d) [25].

The results obtained by Bouallagui et al. show that the Fruit and vegetable waste (FVW) is highly biodegradable with a conventional two-phase reactor and 96% of the total COD was converted to biomass and biogas [26]. Viturtia et al. [27] studied two-phase anaerobic digestion of mixture of fruit and vegetable solid wastes at laboratory scale, using digesters operated in the mesophilic range. Biodegradation achieved in two weeks was around 75%. The process was stable, even when the pH was at the lowest levels (around 5, in the hydrolyzer). Single and two-phase anaerobic digestion of vegetable solid wastes was compared at laboratory scale by Verrier et al. Phase separation under mesophilic conditions resulted in significantly higher methane productivity compared to in a single-stage CSTR reactor [28]. Wei et al. [29] studied that a full-scale jet biogas internal loop anaerobic fluidized bed (JBI-LAFB) reactor (Fig. 2) having active volume of 798 m^3 can treat 33.3 m^3 wastewater per hour. The maximum biogas production and the content of CH_4 in total biogas of the reactor were found to be 80.1 ± 5%, 0.2–0.5, 348.5 m^3/day and 94.5 ± 2.5%, respectively. The prominent characters of this reactor were that the fluidization effect and mass transfer rate was enhanced by biogas recirculation and that microorganism activity was increased by stripping and removing of poisonous gas.

Bühle et al. [30] investigated the digestion dynamics in a continuously working stirrer tank digester at different levels of retention time and volume load suggesting that a stable fermentation of press fluids can only be achieved with retention times of more than 20 days and with volume loads below 2 g VS/l/day. In a continuously working fixed bed digester a steady fermentation could be achieved at a retention time of 8 days and a volume load of 3 g VS/l/day. Acetoclastic methanogenesis in the second stage of a two-phase biogas reactor (Fig. 3) is investigated by Muha et al. [31].

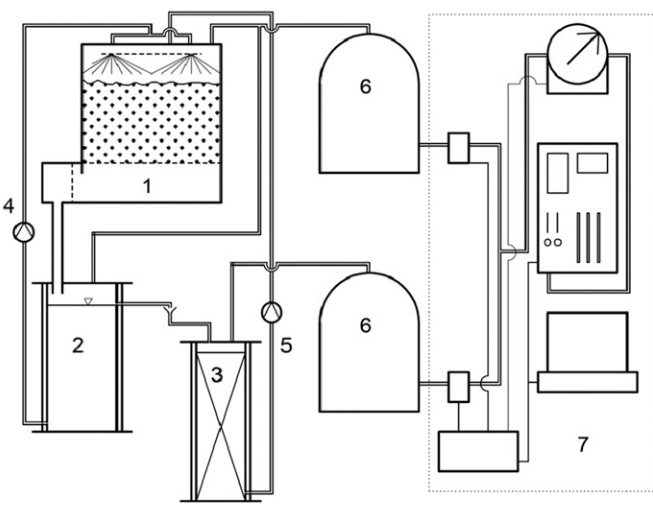

Fig. 3. Scheme of a two-phase laboratory scale anaerobic digestion system described by Muha et al. [31] consisting of: 1. a hydrolysis reactor (100 l), 2. reservoir for leachate from the hydrolysis reactor (60 l), 3. fixed film anaerobic filter (32.12 l), 4.a small leachate circulation system (60 l/ h), 5. complete leachate circulation system (1 l/h), 6. two biogas bags, and 7. Automated gas analysis system.

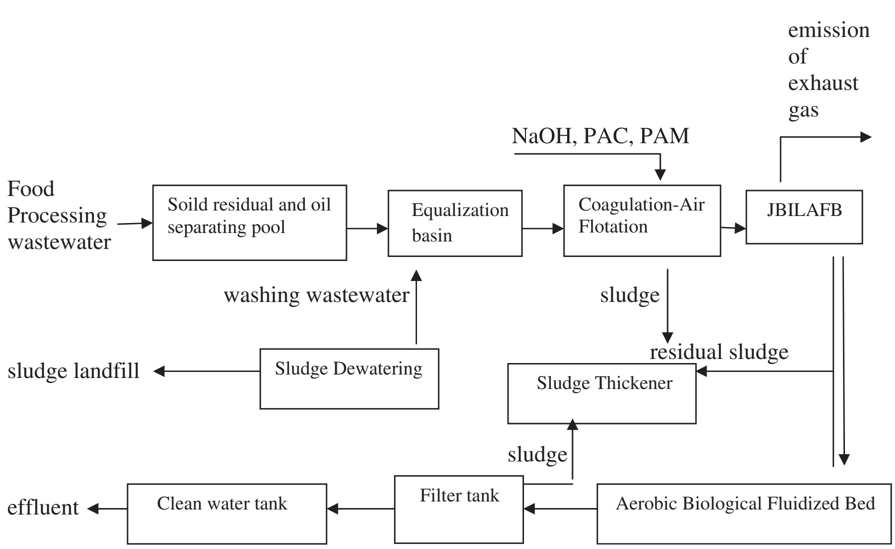

Fig. 2. Process flow diagram of full-scale wastewater treatment plant [29].

A mathematical model coupling chemical reactions with transport of process liquid and with the variation of population of the microorganisms living on the plastic tower packing of the reactor is proposed by them. The evolution of the liquid is described by an advection–diffusion–reaction equation, while a monod-type kinetic is used for the reactions.

3.3. Pre-treatment

Waste is treated and manipulated prior to entering the digester in a process. The goal of pre-treatment is to make the cellulose accessible to hydrolysis for conversion to biogas. Various pre-treatment techniques change the physical and chemical structure of the lignocellulosic biomass and improve hydrolysis rates. Below are discussed techniques which have shown a significant improvement in terms of methane production.

3.3.1. Pre-digestion techniques

Cattle waste slurry was pre-digested and used as feed material for anaerobic digesters thereby increasing biogas production by 17%–19% and methane content from 68%–75% to 75%–86% [32].

Ma et al. [33] found that freeze–thaw pre-treatment was the most profitable process with a net potential profit of around 11.5 € ton^{-1} KW.

3.3.2. Thermochemical

While the carbohydrates and the lipids of the sludge are easily degradable, the proteins are protected from the enzymatic hydrolysis by the cell wall. Heat applied during thermal treatment destroys the chemical bonds of the cell wall and membrane, thus makes the proteins accessible for biological degradation.

Thermal treatment is an effective pretreatment method to disintegrate the sludge cells by applying high temperature. Thermal pre-treatment by Rivero et al. at 90 °C along with oxidative treatment using hydrogen peroxide gave the best results in terms of solids destruction and effluent quality parameters [34].

In thermochemical hydrolysis methods, an acid or base is added to solubilize the sludge. The addition of acid or base avoids the necessity of high temperatures and these methods are thus mostly carried out at ambient or moderate temperatures.

The thermochemical pretreatment studied by Kim et al. [35] showed more than 34.3% increase in methane production and soluble COD (SCOD) removal by more than 67.8% over the control. Biogas production, methane production and the SCOD removal efficiency were about 5037 l biogas/m^3 WAS, 3367 l methane/m^3 WAS and 61.4%, respectively. Various thermo-chemical pre-treatments on water hyacinth increased the solubility of biomass and improved gas production reported by Patel et al. [36]. According to Valo et al. [37] thermo-chemical pre-treatment is the most effective on Chemical Oxygen Demand (COD) solubilization, which could reach 83% at 170 °C with pH = 12. Haug et al. [38] found that methane gas production from digestion of waste activated sludge can be increased by about 60 percent as a result of thermal pre-treatment. Nizami et al. [39] reported that pre-treatment techniques suitable for grass silage include size reduction and thermal treatment such as liquid hot water.

Vivekanand et al. [40] reported that the methane yield from untreated seaweed was 223 ml/g VS, whereas steam explosion pretreated fractions showed a marginal improvement of the yield to values ranging from 260 to 268 ml/g VS. Steam explosion thus had a positive effect on digestion of SW, increasing the methane yield up to 20%. The final methane contents in the biogas produced were in the range 57%–59%.

3.3.3. Radiation and ultrasonic pretreatments

Sonication can be an effective treatment as it is often used to disrupt cell membranes and release cellular contents. Microwave irradiation changes secondary and tertiary structure of proteins of microorganisms. It is an efficient method for disintegrating sludge particles due to fast cell lysis.

The application of sonication for biogasification as pretreatment was studied by various researchers. Saifuddin et al. [41] claimed that the greatest enhancement in methane production was shown by the 3 min microwave plus 10 min ultrasonic treatment.

Microbe cells of sewage sludge were ruptured by γ-irradiation, and it resulted in the release of cytoplasm. The disintegration of the sewage sludge and the rupture of microbe cells releasing soluble carbohydrates could have enhanced the subsequent anaerobic digestion process.

The effect of γ-irradiation pre-treatment on anaerobic digestibility of sewage sludge was investigated by Yuan et al. [42]. Compared with digesters fed with none irradiated sludge, the accumulated biogas production increased 44, 98, and 178 ml for digesters fed sludge irradiated at 2.48, 6.51, and 11.24 kGy, respectively.

Yan et al. [43] found that during the ultrasonic treatment of waste activated sludge (WAS), the mean particle size of WAS decreased from 25.0 to 3.2 μm.

In experiments of Nickel and Neis, ultrasound pre-treatment showed stability in the fermentation of disintegrated sludge with biogas production 2.2 times that of the control fermenter [44].

Park et al. reported that the average biogas production rate with the microwave irradiated sludge at 8, 10, 12, and 15 days HRTs was 240 ± 11, 183 ± 9, 147 ± 8, and 117 ± 7 ml/l/d respectively, while those with the control sludge was 134 ± 12 and 94 ± 7 ml/l/d at 10 and 15 days HRTs. Maximum rates of COD removal and methane production with the pre-treated sludge were 64% and 79% higher than those of the control system, respectively [45].

Hogan et al. [46] claimed that biogas production is increased by ultrasound pre-treatment.

The gas production rates for pre-treated sludge with ultrasound and γ-irradiation were higher than those for untreated sludge [47].

Jung et al. [48] reported that the sewage sludge solubilization rates increased as the ultrasonic time and acoustic density increased. The solubilization rates were enhanced approximately 2.3 times at a dual frequency ultrasonic of 40 W/L.

Kameswari et al. [49] have worked on effect of ozonation and ultrasonication pretreatment processes of tannery solid wastes and found that, application of pretreatment processes enhanced biogas generation by 45% in the case of ozone pre-treated sludge and 53% by ultrasonication processes.

Kim et al. have reported a maximum methane productivity of 0.350 m^3/kg volatile solids (VSs) added from the ultrasonic sludge disintegration of 16% hydrolyzed sludge. Ultrasonic sludge disintegration of 50% produced lower methane production and yields than the sludge of 16 and 30% disintegration. It is thought that excess irradiation of ultrasound converts volatile solids into inert or inhibitory compounds to the methanogenesis [50].

3.3.4. Mechanical pre-treatment

Mechanical treatment employs several strategies for physically disintegrating the cells and partly solubilising their content.

The mechanical methods involve the action of externally applied stress. Results of Baier and Schmidheiny on wet milling prior to anaerobic digestion showed a good digestibility of the solubilised intracellular material and consistently enhanced overall COD-degradation of the sludge by a factor of 1.2–1.5. Net biogas production was enhanced in the same order of magnitude. Stabilized sludge

showed a higher beneficial effect of wet milling than raw excess sludge [51].

Mechanical pre-treatment and combined pre-treatments using six different dosages of hydrogen peroxide (H_2O_2) and ferrous chloride ($FeCl_2$) along with mechanical pre-treatment were conducted by Dhar et al. About 37%–46% removal of H_2S in biogas occurred for different combined pre-treatment conditions. Mechanical pre-treatment increased total cumulative methane production by 8%–10% after 30 days [52].

3.3.5. Chemical (organic and inorganic) pre-treatment

Various organic and inorganic chemicals can be added to the waste to improve gas production. Concentrated acids such as HCl have also been used to treat lignocellulosic materials. Pretreatment with acid hydrolysis can result in improvement of enzymatic hydrolysis of lignocellulosic biomasses. Alkali hydrolysis removes hemicelluloses and lignin and increases accessible surface area.

The total biogas production of per acetic acid pre-treated sludge increased 72% than that of the raw sludge reported by Shang and Hou [53] and 21% enhancement was reported by Lise Appels et al. [54].

Devlin et al. [55] investigated effects of acid pretreatment (pH 6–1) using HCl on subsequent digestion and dewatering of WAS. In semi-continuous digestion experiments (12 days hydraulic retention time at 35 °C) it resulted in a 14.3% increase in methane yield compared to untreated WAS.

Dewil et al. [56] studied several peroxidation techniques to increase the biogas production. A maximum increase of 75% was measured with Fenton, while the peroxymonosulfate (POMS) treatment increased the biogas production by a factor of nearly 2, against an even higher 2.5 for the dimethyldioxirane (DMDO) treatment.

In the semi-continuous digesters using iron-enriched duckweed as a supplement, an increase in gas production of about 44% was observed by Clark et al. [57].

Rao et al. reported that addition of 20 mM $FeSO_4$ to the daily-fed cow dung and poultry litter waste digesters, increased methanogenesis by 40% and 42%, respectively [58].

More than 60% increase in gas production was observed by Patel et al., on addition of $FeCl_3$ in anaerobic digestion of water hyacinth-cattle dung [59].

Hansen et al. reported that addition of 1.5% (w/w) activated carbon, 10% (w/w) glauconite or 1.5% (w/w) activated carbon and 10% (w/w) glauconite resulted in an increase of the methane yield to 126 ml CH_4/g VS, 90 ml CH_4/g VS and 195 ml CH_4/g-VS respectively [60].

Patel et al. [61] found a trend of enhanced gas production with high methane content and lower effluent BOD and COD, by increasing doses of the added adsorbents gelatin, polyvinyl alcohol, powdered activated charcoal, pectin, kaolin, silica gel, aluminium powder, bentonite and talc powder in anaerobic digestion of water hyacinth cattle dung.

Ram et al. [62] observed that addition of 20 mM sulfate enhanced biogas production two-fold at 10 and 20 °C.

Anand et al. reported that charcoal coating of ground around the digester is shown to improve gas production from the KVIC biogas plant by 7%–15% [63].

Nickel is stimulatory (Geeta et al.) in biogas production up to 5 ppm, with an optimum at 2.5 ppm, in a water hyacinth–bovine excreta substrate [64].

Desai et al. [65] claimed that about a two-fold enhancement in total gas production with 17% enriched methane content was achieved with the addition of 4 g/l of silica gel as adsorbent.

Anaerobic digestion of water hyacinth-cattle dung (Madamwar et al.) was improved by addition of mixtures of surfactant–surfactant, adsorbent–adsorbent and surfactant–adsorbent. Among the combinations tested, bentonite and gelatin, gelatin and Tegoprens 43, sodium lauryl sulfate and Tegoprens 42, and Tegoprens 47 and Tegoprens 63 showed more than a 100% increase in gas production with higher methane yield [66]. In anaerobic digestion process of water hyacinth-cattle dung, addition of surfactant Tegoprens 43 showed a maximum of more than 114% increase in gas production with a 6.25% higher methane content [67].

Sodium lauryl sulfate as surfactant showed a 70% increase in gas production with higher methane content (77%) and improved biodegradation in anaerobic digestion process of salty cheese whey in experiments of Patel et al. [68].

Chakraborty et al. reported that clay anchored enzymes showed 10 times increase in gas generation rate as compared to raw cow dung slurry and about 75% methane enrichment by increasing the methane to carbon dioxide ratio from 1.5 to 2.66 [5].

Pakarinen et al. [69] reported that production of methane from urea-treated hemp increased by 25% to 42% compared to the yield from the fresh material. There was substantially increase in methane yields from maize, exceeding that obtained from fresh material. Use of formic acid in ensiling of maize enhanced the methane yields even further, increasing after 4 months ensiling to 455 dm^3 CH_4/kg VS, that is, by 16% from 393 dm^3 CH_4/kg VS, obtained from the fresh material.

The alkaline and autoclaving pretreatment of switchgrass increased the methane production gain, from 32 to 61% [22].

3.3.6. Plant biomass

Plant biomass is a biological additive which include different plants, weeds etc. They are available naturally in the surroundings and help in improving anaerobic digestion. Plant biomass is mainly composed of cellulose, hemicellulose, and lignin. The composition of these constituents can vary from one plant species to another. Cellulose and hemicelluloses are easily degradable compared to lignin present in the plant biomass leading to increase or decrease of biogas production.

The methane content of the gas varied between 60% and 70% by addition of *Parthenium hysterophorus*, a weed with cattle manure at 10% level reported by Gunaseelan et al. [70].

Darand Tandon [71] evaluated the contribution of alkali-treated plant residues as a supplement to cattle dung for biogas production. Lantana slurry gave 63.6% methane in the biogas; apple leaf litter, 59.6%, wheat straw, 58%, and peach leaf litter, 57.7%, against cattle dung, 56.1%. The digestion efficiency in terms of biogas release per gram of dry matter with pre-treated plant residues was 341–372 ml/g, 31%–42% higher than cattle dung.

Mixtures of partially decomposed Ageratum and cattle dung (Kalia et al.) yielded about 9% more biogas than did pure cattle dung. The methane contents of the gas obtained from Ageratum mixtures were 62%–77% as compared to 56%–60% from pure cattle dung [72].

Powdered leaves of some plants and legumes (like Gulmohar, Leucacena leucocephala, Acacia auriculiformis, Dalbergia sisoo and Eucalyptus tereticonius) have been found to stimulate biogas production between 18% and 40% [73,74,75].

According to Manoni Mshandete et al. [76] sisal fiber waste is a novel promising biofilm carrier for bioreactors treating sisal leaf tissue waste leachate. It has the chemical oxygen demand (COD) removal efficiencies in the range of 80%–93% at OLRs in the range of 2.4–25 g COD/L/d.

3.3.7. Microbial additives

Different strains of bacteria and fungi have been found to enhance gas production.

These microbes degrade lignin and hemicelluloses in waste materials. This safe and environmentally friendly method is increasingly being advocated as a process that does not require high energy for lignin removal from a lignocellulosic biomass, despite

extensive lignin degradation. Lignin degradation by white-rot fungi occurs through the action of Lignin-degrading enzymes such as peroxidases and laccase. These enzymes are regulated by carbon and nitrogen sources.

Anaerobic digestion experiments by Zhong et al. [77] showed that the biogas productivity was increased by pre-treatments of corn straw using Fungus *Pleurotus florida* and chemicals such as NaOH, ammonia, and urea. Biogas production after NaOH treatment was 207.07% higher than the raw corn straw.

Pre-treatment of the olive-mill wastewater (OMW) with a white-rot fungus *Pleurotus ostreatus* for removal of the contained phenolics, allowed a stable operation at an HRT of 30 days [78].

Production of methane was 95% greater than the control by the addition of lyophilized bacilli and the combination of micronutrients (Fe, Co, Ni and Mo) with bacilli showed a better methane production than the control, 167% higher in day 17 [79].

Pretreatment of orange processing waste (OPW) by solid-state fermentation using selected strains of *Sporotrichum*, *Aspergillus*, *Fusarium* and *Penicillium* improved the overall productivity of biogas and methane [80].

The gas production by addition of microbial stimulant Aquasan® at 15 ppm was 39% and 55% higher with single and dual additions, respectively, than untreated cattle dung. In another bench scale study (1:1 dry matter) the addition of Teresan® at 10 ppm concentration to the mixed residues of cattle dung and kitchen wastes at different solids concentration, produced 34.8% more gas (272.4 l/kg d.m.) than the uninoculated mixture at 15% TS concentration (202.4 l/kg d.m.) [81].

Biological treatment of the recalcitrant organic matter (biofibers) of the manure with the hemicelluloses degrading bacterium B4 resulted in a significant increase of the biogas potential of manure. An increase of approximately 30% in methane potential was achieved compared to controls [82].

Miah et al. [83] reported enhanced biogas production on sewage sludge by a culture of the AT1 strain that is closely related to *Geobacillus thermodenitrificans*. They obtained a reduction of 21% in volatile solids.

Cellulolytic strains of bacteria like actinomycetes and mixed consortia have been found to improve biogas production in the range of 8.4%–44% from cattle dung [73,84,85].

Aydinol et al. [86] depicted that with a hydraulic retention time of 24 h, highest total chemical oxygen demand (TCOD) removal with an extracellular enzyme dosage of 0.2 mL/L. In the activation period of the extracellular enzyme (on days 186–212), enhancement in TCOD removal was from 69.3% (without enzyme) to 81.9% (with enzyme).

Enzymatic extract preparation from *Pseudomonas aeruginosa* KM110 under accession no. HQ730879 with lipase activity (0.3 U/ml), was used to perform enzymatic hydrolysis pretreatment of asynthetic dairy wastewater with 1000 mg/L total fat content. The pretreatment was optimized for 48 h hydrolysis time by Qamsari et al. [87]. Both raw and prehydrolyzed wastewaters were digested in a batch bioreactor, biogas produced after 13 days was 2330 ml and 4710 ml respectively.

Takačova et al. [88] reported that aerobic pre-treatment of the Prunus serulata foliage substrate assisted by lignolytic fungus *Pleurotus pulmonarius* led to five times higher methane yield in comparison to that obtained from the untreated substrate.

The goal of pretreatment in biomass-to-biofuels conversion is depicted in Fig. 4 by Kumar et al. [89].

3.4. Factors/Control parameters

Variation in parameters like pH, temperature, hydraulic retention time, CN ratio, organic loading rate etc., can affect the biogas production.

Most microorganisms grow best under neutral pH conditions, since other pH values may adversely affect metabolism by altering the chemical equilibrium of enzymatic reactions, or by actually destroying the enzymes.

Two main temperature ranges for anaerobic digestion are: Mesophilic (20–45 °C) and Thermophilic (50–65 °C).

Anaerobic digestion needs long time for digestion and its decomposition efficiency is low. Hence, for the enhancement of anaerobic digestion efficiency, longer HRT is required.

The relationship between the amount of carbon and nitrogen present in the organic materials is represented by C:N ratio. Optimum C:N ratio is between 20 and 30.

Application of an extruder on agricultural biomass increased the methane yield significantly: by 18%–70% after 28 days, and by 9%–28% after 90 days [90].

Hyaric et al. [91] found that propionate concentration and moisture content strongly influenced the specific methanogenic activity (SMA). The highest SMA was observed at a substrate concentration of 10 g COD/kg and at a moisture content of 82%.

Meher et al. [7] isolated *Syntrophobacter wolinii* a propionate degrading bacterium in co-culture with hydrogen utilizing methanogen viz., *Methanobacterium formicicum* from the fermenting slurry of cattle dung biogas plant. The coculture isolated showed 7.0 to 7.5 pH requirement for its optimal growth and 35 °C for its maximal activity.

An increase in sludge surface area improves the anaerobic digestion of primary sludge [92].

Biogas production from the experimental thermophilic digester was higher on average than from psychrophilic and mesophilic

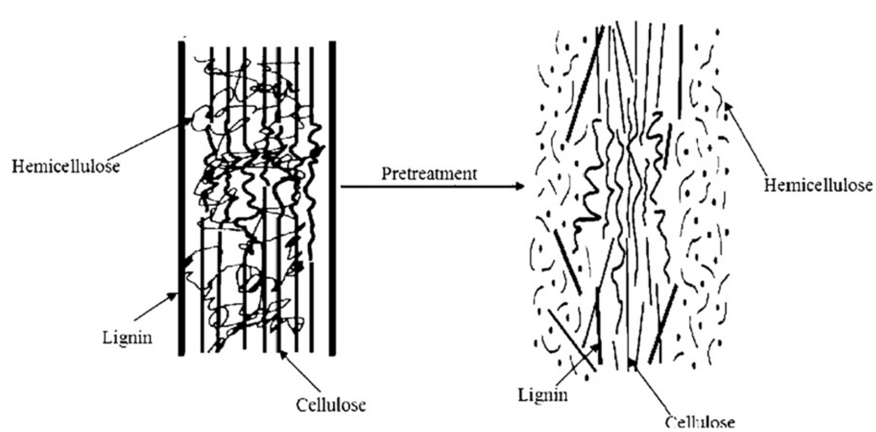

Fig. 4. Schematic of the role of pretreatment in the conversion of biomass to fuel.

digesters by 144 and 41%, respectively. The net energy production in the thermophilic digester was 195.7 and 49.07 kJ per day higher than that for the psychrophilic and mesophilic digesters, respectively [93].

Hills [94] in his experiment found that the greatest methane production per unit loading rate occurred when the C:N ratio of the feed was 25.

Kim et al. [95] found that maximum biogas production occurred when a hydraulic retention time (HRT) of 10 d was used and methane yield was the highest in the reactor when an HRT of 12 d was used (223l CH_4/kg s COD degraded).

Jeyapriya et al. [96] found that maximum biogas was produced only when the pH value was close to neutral value.

Castillo et al. [97] found that there is a three times increase in methane production from sludge of waste water treatment plant by increasing the temperature to 15 °C above room temperature.

Cecchi et al. [98] verified that increased external temperature caused the transformation of the ethanol contained in the source sorted organic fraction of municipal solid waste fed to the digester, into acetate. The kinetic constant for the first order substrate utilization model in the summer (external temperature greater than 18–20 °C) doubled with respect to the winter, although the digester was held at 35 ± 2 °C throughout.

Maximum methane production (0.64 l/l of digester/d) in anaerobic digestion of water hyacinth cattle dung was found with a retention time between 7 and 9 d at 35 °C, and a 7 to 9% (w/v) total solid content of water hyacinth-cattle dung (7:3 w/w) [99].

Bouallagui et al. [100] reported that by applying a feed concentration of 6% and HRT of 20 days in the tubular digester, 75% conversion efficiency of FVW into biogas with a methane content of 64% was achieved.

Hashimoto [101] found that methane yield lowered drastically at inoculum/substrate ratios (on a volatile solids basis) below 0.25. Methane production rate increased at a decreasing rate up to an inoculum/substrate ratio of two, after which it remained relatively constant.

A decrease in the C:N ratio from 40 to about 27 by the addition of urea and diammonium phosphate (DAP) showed a slight (8%–11%) improvement in anaerobic digestion of cattle waste for biogas production [102].

The presence of aerobic cell lysate in thickened excess activated sludge caused an improvement in the methane yield ranging from 8.1 to 86.4% dependent on the sludge quality [103].

Azbar et al. [104] worked on organic loading in terms of COD rate for treating olive mill effluent and found that up-flow anaerobic sludge blanket reactor could tolerate high influent COD concentrations i.e. up to 109,800 COD (mg/L) and with 90% of removal.

Devi et al. [105] reported that the gas generation was high under recirculation of leachate into the reactor in their study on solid phase anaerobic digestion of MSW. Morita et al. [106] discussed in his paper that the surface hydrophobicity and porosity of supporting materials are important factors in retaining microorganisms such as aceticlastic methanogens and in attaining a higher degradation of garbage and a higher production of biogas.

4. Conclusion

Anaerobic digestion is a renewable energy source which can comfortably replace fossil fuel as an environment friendly process. Literature analysis reveals that biogas production can be enhanced using different techniques. Codigestion is one of the interesting options for improving biogas yield. Bioreactor design is an important factor in improving anaerobic digestion; two-phase digester gives high yield compare to single phase digester. Various pre-treatment methods for improving biogas production have been discussed here. Enhancement is seen by addition of different additives, microbial strains and plant biomass. Proper control of various operational parameters i.e. C:N ratio, pH, and hydraulic retention time etc, helps in enhancement of anaerobic digestion.

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